

# Higgs precision study of the 750 GeV diphoton resonance and the 125 GeV standard model Higgs boson with Higgs-singlet mixing

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## Abstract

We interpret the potential observation of the 750 GeV di-photon resonance at the LHC in models, in which an  $SU(2)$  isospin-singlet scalar boson mixes with the Standard Model (SM) Higgs boson through an angle  $\alpha$ . Allowing the singlet scalar boson to have renormalizable couplings to vector-like leptons and quarks and introducing sizable decay width of the 750 GeV di-photon resonance into non-SM particles such as dark matters, we can explain the large production cross section  $\sigma(H_2) \times B(H_2 \rightarrow \gamma\gamma)$  as well as the apparent large total width of the boson without conflicts from the results obtained by previous global fits to the SM Higgs boson data.

## I. INTRODUCTION

The biggest triumph of the LHC Run I was the discovery of the Standard Model (SM) like Higgs boson with mass about 125 GeV [1, 2]. The signal-strength data and the spin-parity of the observed 125 GeV particle have all indicated that it is very close to the SM Higgs boson [3, 4]. After a shutdown for 2 years, the Run II started with a high expectation. Just with an accumulated luminosity of about  $3 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$ , both ATLAS [5] and CMS [6] showed a hint of a new particle at about 750 GeV decaying into a photon pair. The particle is likely to be a scalar boson or a spin-2 particle. We focus on the scalar boson scenario in this paper.

With a luminosity of  $3.2 \text{ fb}^{-1}$ , the ATLAS Collaboration found a resonance structure at  $M_X \approx 750 \text{ GeV}$  with a local significance of  $\sim 3.64\sigma$ , but corresponding to  $1.88\sigma$  when the look-elsewhere-effect is taken into account [5]. The CMS Collaboration also reported a similar though smaller excess with a luminosity of  $2.6 \text{ fb}^{-1}$  at  $M_X \approx 760 \text{ GeV}$  with a local significance of  $2.6\sigma$  but a global significance less than  $1.2\sigma$  [6]. Also, in the analysis of ATLAS a total width of about 45 GeV is preferred [5].

These data could be summarized as follows:

$$\text{ATLAS : } M_X = 750 \text{ GeV, } \sigma_{\text{fit}}(pp \rightarrow X \rightarrow \gamma\gamma) \approx 10 \pm 3 \text{ fb; (95\% CL), } \Gamma_X \approx 45 \text{ GeV}$$

$$\text{CMS : } M_X = 760 \text{ GeV, } \sigma_{\text{fit}}(pp \rightarrow X \rightarrow \gamma\gamma) \approx 9 \pm 7 \text{ fb; (95\% CL)}$$

The uncertainties shown are  $1.96\sigma$  corresponding to 95% CL. Note that we estimate the best-fit cross section from the 95%CL upper limits given in the experimental paper, by subtracting the “expected” limit from the “observed” limit at  $M_X = 750$  (760) GeV for ATLAS (CMS).

Although this hint for a new resonance is still very preliminary, it has stimulated a lot of phenomenological activities, bringing in a number of models for interpretation. The first category is the Higgs-sector extensions, including adding singlet Higgs fields [7–9], two-Higgs-doublet models and the MSSM [10]. But in general it fails to explain the large production cross section of  $pp \rightarrow H \rightarrow \gamma\gamma$  in the conventional settings, unless additional particles are added, for example, vector-like fermions [7–10]. Another category is the composite models [11] that naturally contain heavy fermions, through which the production and the di-photon decay of the scalar boson can be enhanced. Other possibilities are also entertained, such as

axion [12], sgoldstini [13], radion/dilaton [14], and other models [15]. More general discussion of the di-photon resonance or its properties can be found in Refs. [16]. The generic feature of the suggested interpretations is to enhance the production cross section of  $pp \rightarrow H \rightarrow \gamma\gamma$ , where  $H$  is the 750 GeV scalar or pseudo-scalar boson, by additional particles running in the  $H\gamma\gamma$  decay vertex and/or  $Hgg$  production vertex. Another generic feature though not realized in the CMS data is the relatively broad width of the particle, which motivates the idea that this particle is window to the dark sector or dark matter [8, 9].

A possible interpretation for this 750 GeV particle can be an  $SU(2)$  isospin-singlet scalar. In this interpretation, a general feature is that the singlet  $s$  mixes with the SM Higgs doublet  $H_{\text{SM}}$  through an angle  $\alpha$  due to the cubic and quartic potential terms such as  $\mu s H_{\text{SM}}^\dagger H_{\text{SM}} + \lambda s^2 H_{\text{SM}}^\dagger H_{\text{SM}}$ . Further, we note that the singlet may also have renormalizable couplings to new vector-like leptons and quarks [17]. We assume after mixing the lighter boson is the observed SM-like Higgs boson  $H_1$  at 125 GeV while the heavier one  $H_2$  is the one hinted at 750 GeV. Thus, the 750 GeV scalar boson  $H_2$  opens the window to another sector containing perhaps dark matter (DM) and other exotic particles.

In our previous global fits to the Higgs-portal type models with the SM Higgs mixing with a singlet scalar boson with all the Higgs boson data from Run I [18], we have constrained the parameter space of a few models with a singlet scalar. In the Higgs-portal singlet-scalar models with hidden sector DM, there are no new contributions to the  $h\gamma\gamma$  and  $hgg$  vertices beyond the SM contributions, and the mixing angle  $\alpha$  is constrained to  $\cos \alpha > 0.86$  at 95% CL. However, in those models with vector-like leptons (quarks) the mixing angle can be relaxed to  $\cos \alpha > 0.83$  (0.7) at 95% CL.

The implication is that the 750 GeV scalar boson  $H_2$  can be produced in  $gg$  fusion as if it were a 750 GeV SM Higgs boson but with a suppression factor  $\sin^2 \alpha$  if there are no vector-like quarks running in the  $H_2 gg$  vertex. Additional contributions arise when there are vector-like quarks running in the loop. Similarly, the decay of the scalar boson  $H_2$  behaves like a 750 GeV SM Higgs boson with each partial width suppressed by  $\sin^2 \alpha$  if there are no vector-like leptons or quarks running in the  $H_2 gg$  and  $H_2 \gamma\gamma$  vertices. If this is the case the branching ratio  $B(H_2 \rightarrow \gamma\gamma) \sim 10^{-6}$ , which is too small to explain the resonance. In this work, we consider vector-like leptons and vector-like quarks that can enhance the  $H_2 \rightarrow \gamma\gamma$  decay substantially to give a large production cross section for  $pp \rightarrow H_2 \rightarrow \gamma\gamma$ .

Vector-like fermions are quite common in a number of extensions of the SM with var-

ious motivations. Although we can introduce vector-like fermions in an *ad hoc* and phenomenological way in order to explain the 750 GeV diphoton excess, their existence can be understood at theoretically deeper levels. They appear naturally in models with new chiral  $U(1)$  gauge symmetries in order to cancel gauge anomalies [19–21], in non-Abelian gauge extensions such as  $SU(3)_C \times SU(3)_L \times U(1)_Y$  model (the so-called 3-3-1 model where gauge anomalies cancel when three generations of fermions are considered) [22], or in flavor models for fermion masses and mixing [23], to name a few explicit models in the context of 750 GeV diphoton excess. In such models, one can in particular forbid large bare masses of the vector-like fermions if they are chiral under this new  $U(1)$  gauge symmetries, and thus motivate their masses fall into the range we need to accommodate the 750 GeV diphoton excess.

In this paper, we interpret the 750 GeV di-photon resonance by introducing an  $SU(2)$  singlet taking fully account of its mixing with the SM doublet. We show that the large production cross section can be explained if the singlet scalar has renormalizable couplings to the vector-like leptons and quarks. We further show the possibly large total width can be accommodated if  $H_2$  substantially decay into non-SM particles such as dark matters.

The organization is as follows. In the next section, we describe briefly the framework of the SM Higgs mixing with a singlet scalar that couples to new vector-like fermions. In Sec. III, we present the numerical results for the 750 GeV resonance including the constraints from the properties of the 125 GeV SM Higgs-like scalar boson. Then we conclude in Sec. IV.

## II. HIGGS-SINGLET MIXING FRAMEWORK

If there are extra vector-like fermions with renormalizable couplings to a singlet scalar  $s^*$ , these models generically contain two interaction eigenstates  $h$  denoting the remnant of the SM Higgs doublet and  $s$  the singlet. The two mass eigenstates  $H_{1,2}$  are related to the states  $h$  and  $s$  through an  $SO(2)$  rotation as follows:

$$H_1 = h \cos \alpha - s \sin \alpha; \quad H_2 = h \sin \alpha + s \cos \alpha \quad (1)$$

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\* This singlet scalar  $s$  could be a remnant of new gauge symmetry breaking. In that case,  $s$  may carry a new quantum number different from the SM gauge charges [24].

with  $\cos \alpha$  and  $\sin \alpha$  describing the mixing between the interaction eigenstates  $h$  and  $s$ . In the limit of  $\sin \alpha \rightarrow 0$ ,  $H_1$  ( $H_2$ ) becomes the pure doublet (singlet) state. In this work, we are taking  $H_1$  for the 125 GeV boson discovered at the 8-TeV LHC run and  $H_2$  for the 750 GeV state hinted at the early 13-TeV LHC run. We are taking  $\cos \alpha > 0$  without loss of generality. For the detailed description of this class of models and also Higgs-portal models, we refer to Refs. [17, 18].

In this class of models, the singlet field  $s$  does not directly couple to the SM particles, but only through the mixing with the SM Higgs field at renormalizable level. And the Yukawa interactions of  $h$  and  $s$  are described by

$$-\mathcal{L}_Y = h \sum_{f=t,b,\tau} \frac{m_f}{v} \bar{f}f + s \sum_{F=Q,L} g_{s\bar{F}F}^S \bar{F}F, \quad (2)$$

with  $f$  denoting the 3rd-generation SM fermions and  $F$  the extra vector-like fermions (VLFs): vector-like quarks (VLQs) and vector-like leptons (VLLs). Then the couplings of the two mass eigenstates  $H_{1,2}$  to the SM and extra fermions are given by

$$\begin{aligned} -\mathcal{L}_Y = & H_1 \left[ \cos \alpha \sum_{f=t,b,\tau} \frac{m_f}{v} \bar{f}f - \sin \alpha \sum_{F=Q,L} g_{s\bar{F}F}^S \bar{F}F \right] \\ & + H_2 \left[ \sin \alpha \sum_{f=t,b,\tau} \frac{m_f}{v} \bar{f}f + \cos \alpha \sum_{F=Q,L} g_{s\bar{F}F}^S \bar{F}F \right]. \end{aligned} \quad (3)$$

The couplings of  $H_{1,2}$  to two gluons, following the conventions and normalizations of Ref. [25], are given by

$$\begin{aligned} S_{H_1}^g &= \cos \alpha S_{H_1}^{g(\text{SM})} - \sin \alpha S_{H_1}^{g(Q)} \\ &\equiv \cos \alpha \sum_{f=t,b} F_{sf}(\tau_{1f}) - \sin \alpha \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q} F_{sf}(\tau_{1Q}), \\ S_{H_2}^g &= \sin \alpha S_{H_2}^{g(\text{SM})} + \cos \alpha S_{H_2}^{g(Q)} \\ &\equiv \sin \alpha \sum_{f=t,b} F_{sf}(\tau_{2f}) + \cos \alpha \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q} F_{sf}(\tau_{2Q}), \end{aligned} \quad (4)$$

where  $\tau_{ix} = M_{H_i}^2/4m_x^2$ . We note that  $S_{H_1}^{g(\text{SM})} \simeq 0.651 + 0.050i$  for  $M_{H_1} = 125.5$  GeV and  $S_{H_2}^{g(\text{SM})} \simeq 0.291 + 0.744i$  for  $M_{H_2} = 750$  GeV. In the limit  $\tau \rightarrow 0$ ,  $F_{sf}(0) = 2/3$ . The mass of extra fermion  $F$  may be fixed by the relation  $m_F = v_s g_{s\bar{F}F}^S + m_F^0$  where  $v_s$  denotes the VEV of the singlet  $s$  while  $m_F^0$  is generated from a different origin other than  $v_s$  as in  $-\mathcal{L}_{\text{mass}} \supset m_F^0 \bar{F}F$ . We note that, when  $m_Q^0 = 0$ , each contribution from a VLQ is not suppressed by  $1/m_Q$  but by the common factor  $1/v_s$ .

Similarly, the couplings of  $H_{1,2}$  to two photons are given by

$$\begin{aligned}
S_{H_1}^\gamma &= \cos \alpha S_{H_1}^{\gamma(\text{SM})} - \sin \alpha S_{H_1}^{\gamma(F)} \\
&\equiv \cos \alpha \left[ 2 \sum_{f=t,b,\tau} N_C Q_f^2 F_{sf}(\tau_{1f}) - F_1(\tau_{1W}) \right] - \sin \alpha \left[ 2 \sum_F N_C Q_F^2 g_{s\bar{F}F}^S \frac{v}{m_F} F_{sf}(\tau_{1F}) \right], \\
S_{H_2}^\gamma &= \sin \alpha S_{H_2}^{\gamma(\text{SM})} + \cos \alpha S_{H_2}^{\gamma(F)} \\
&\equiv \sin \alpha \left[ 2 \sum_{f=t,b,\tau} N_C Q_f^2 F_{sf}(\tau_{2f}) - F_1(\tau_{2W}) \right] + \cos \alpha \left[ 2 \sum_F N_C Q_F^2 g_{s\bar{F}F}^S \frac{v}{m_F} F_{sf}(\tau_{2F}) \right],
\end{aligned} \tag{5}$$

where  $N_C = 3$  and 1 for quarks and leptons, respectively, and  $Q_{f,F}$  denote the electric charges of fermions in the unit of  $e$ . In the limit  $\tau \rightarrow 0$ ,  $F_1(0) = 7$ . We note that  $S_{H_1}^{\gamma(\text{SM})} \simeq -6.55 + 0.039i$  for  $M_{H_1} = 125.5$  GeV and  $S_{H_2}^{\gamma(\text{SM})} \simeq -0.94 - 0.043i$  for  $M_{H_2} = 750$  GeV.

The production cross section of  $H_2$  via the gluon-fusion process is given by

$$\sigma(gg \rightarrow H_2) = \frac{|S_{H_2}^g|^2}{|S_{H_2}^{g(\text{SM})}|^2} \sigma_{\text{SM}}(gg \rightarrow H_2) \tag{6}$$

with  $\sigma_{\text{SM}}(gg \rightarrow H_2) \approx 800$  fb denoting the corresponding SM cross section for  $M_{H_2} = 750$  GeV at  $\sqrt{s} = 13$  TeV [26]. Note that the relation in Eq. (6) only holds at leading order.

The total decay width of  $H_2$  can be cast into the form

$$\Gamma(H_2) = \sin^2 \alpha \Gamma_{\text{SM}}(H_2) + \Delta\Gamma_{\text{vis}}^{H_2} + \Delta\Gamma_{\text{inv}}^{H_2}, \tag{7}$$

where  $\Gamma_{\text{SM}}(H_2) \simeq 250$  GeV for the SM-like  $H_2$  with  $M_{H_2} = 750$  GeV<sup>†</sup>. And  $\Delta\Gamma_{\text{vis}}^{H_2}$  and  $\Delta\Gamma_{\text{inv}}^{H_2}$  denote additional partial decay widths of  $H_2$  into visible and invisible particles, respectively. The quantity  $\Delta\Gamma_{\text{vis}}^{H_2}$  includes the decays into  $H_1 H_1$  by definition and, if it is allowed kinematically, into extra vector-like fermions as well as those into  $\gamma\gamma$ ,  $gg$  through the one-loop processes induced by the extra VLQs and/or VLLs. The quantity  $\Delta\Gamma_{\text{inv}}^{H_2}$  may include the  $H_2$  decay into invisible particles such as dark matters, or  $H_2$  decays into a pair of Nambu-Goldstone bosons such as Majorons which appear in models for neutrino mass generations (see Refs. [28, 29] for example), or dark radiation (or fractional cosmic neutrinos) which appear when global dark  $U(1)$  symmetry is spontaneously broken [30].

The partial decay width of  $H_2$  into two photons is given by

$$\Delta\Gamma_{\text{vis}}^{H_2 \rightarrow \gamma\gamma} = \frac{M_{H_2}^3 \alpha^2}{256 \pi^3 v^2} \left[ |S_{H_2}^\gamma|^2 - \sin^2 \alpha |S_{H_2}^{\gamma(\text{SM})}|^2 \right] \tag{8}$$

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<sup>†</sup> For  $M_{H_2} = 750$  GeV,  $\Gamma_{\text{SM}}(H_2 \rightarrow WW) \simeq 145$  GeV,  $\Gamma_{\text{SM}}(H_2 \rightarrow ZZ) \simeq 71.9$  GeV, and  $\Gamma_{\text{SM}}(H_2 \rightarrow t\bar{t}) \simeq 30.6$  GeV. [27].

and that into two gluons is

$$\Delta\Gamma_{\text{vis}}^{H_2 \rightarrow gg} = \left[1 + \frac{\alpha_s}{\pi} \left(\frac{95}{4} - 7\right)\right] \frac{M_{H_2}^3 \alpha_s^2}{32\pi^3 v^2} \left[|S_{H_2}^g|^2 - \sin^2 \alpha |S_{H_2}^{g(\text{SM})}|^2\right] \quad (9)$$

with  $\alpha_s = \alpha_s(M_{H_2})$ .

### III. NUMERICAL RESULTS

In our numerical analysis, we shall restrict ourselves to the case  $2m_F > M_{H_2}$  so that  $H_2 \rightarrow F\bar{F}$  decays are kinematically forbidden and  $S_{H_1, H_2}^{g(Q), \gamma(F)}$  are all real. In this case, one may carry out a model-independent study on the 750 GeV di-photon resonance with the following varying parameters:

$$\sin \alpha, \quad S_{H_2}^{g(Q)}, \quad S_{H_2}^{\gamma(F)}, \quad \Gamma_{H_2}^{\text{non-SM}}, \quad \eta^{g(Q)}, \quad \eta^{\gamma(F)}, \quad (10)$$

where

$$\Gamma_{H_2}^{\text{non-SM}} \equiv \Gamma(H_2 \rightarrow H_1 H_1) + \Delta\Gamma_{\text{inv}}^{H_2}. \quad (11)$$

Here the parameters  $\eta^{g(Q)}$  and  $\eta^{\gamma(F)}$  are defined as in

$$S_{H_1}^{g(Q)} \equiv \eta^{g(Q)} S_{H_2}^{g(Q)}, \quad S_{H_1}^{\gamma(F)} \equiv \eta^{\gamma(F)} S_{H_2}^{\gamma(F)}. \quad (12)$$

We note that  $\eta^{g(Q)}$  and  $\eta^{\gamma(F)}$  take values between 2/3 and 1 for the following reasons:

$$\begin{aligned} S_{H_1}^{g(Q)} &= \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q} F_{sf}(\tau_{1Q}) \simeq \frac{2}{3} \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q}, \\ \frac{2}{3} \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q} &\leq S_{H_2}^{g(Q)} = \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q} F_{sf}(\tau_{2Q}) \leq \sum_Q g_{s\bar{Q}Q}^S \frac{v}{m_Q}, \end{aligned} \quad (13)$$

if we have  $g_{s\bar{Q}Q}^S > 0$  for all  $Q$ 's<sup>‡</sup>.

Since  $|S_{H_1}^{g(Q), \gamma(F)}|$  is larger than  $\frac{2}{3} |S_{H_2}^{g(Q), \gamma(F)}|$ , the parameters  $S_{H_2}^{g(Q), \gamma(F)}$  can not be arbitrarily large without affecting the LHC data on 125 GeV Higgs boson when  $\sin \alpha \neq 0$ . For example, the quantities

$$C_{H_1}^{g, \gamma} = |S_{H_1}^{g, \gamma}| / |S_{H_1}^{g, \gamma(\text{SM})}| \quad (14)$$

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<sup>‡</sup> In this study, we take the more conventional choice of  $g_{s\bar{F}F}^S > 0$  for the Yukawa-type coupling between  $s$  and VLFs. In general, it may be possible to have negative  $g_{s\bar{F}F}^S$  for some VLFs in specific models and the parameters  $\eta^{g(Q), \gamma(F)}$  can take any values in principle. However, we shall fully investigate such a case in a later work [31].

can not significantly deviate from 1 [3]. If  $\sin \alpha |S_{H_1}^{g(Q)}|$  and  $\sin \alpha |S_{H_1}^{\gamma(F)}|$  are required to be within the  $\pm 10\%$  range of the corresponding SM values, one might have

$$|S_{H_2}^{g(Q)}| \lesssim \frac{0.1}{|\sin \alpha|}, \quad |S_{H_2}^{\gamma(F)}| \lesssim \frac{1}{|\sin \alpha|}, \quad (15)$$

when  $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$ . Therefore, we again restricted ourselves to the case of  $|\sin \alpha| \lesssim 0.1$  in order to have  $|S_{H_2}^{g(Q)}| \gtrsim \mathcal{O}(1)$  and  $|S_{H_2}^{\gamma(F)}| \gtrsim \mathcal{O}(10)$ .

When  $\sin \alpha \sim 0$ , we have numerically

$$\begin{aligned} \sigma(gg \rightarrow H_2) &\sim 1250 |S_{H_2}^{g(Q)}|^2 \text{ fb}, \\ \Gamma(H_2 \rightarrow \gamma\gamma) &\sim 4.67 \times 10^{-5} |S_{H_2}^{\gamma(F)}|^2 \text{ GeV}, \\ \Gamma(H_2 \rightarrow gg) &\sim 8.88 \times 10^{-2} |S_{H_2}^{g(Q)}|^2 \text{ GeV}, \\ \sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow \gamma\gamma) &\sim 11.8 \frac{(|S_{H_2}^{g(Q)} S_{H_2}^{\gamma(F)}|/90)^2}{(\Gamma_{H_2}/40 \text{ GeV})} \text{ fb} \end{aligned} \quad (16)$$

where  $\Gamma_{H_2} \sim \Gamma(H_2 \rightarrow \gamma\gamma) + \Gamma(H_2 \rightarrow gg) + \Gamma(H_2 \rightarrow H_1 H_1) + \Delta\Gamma_{\text{inv}}^{H_2}$ .

First of all, to have  $\Gamma(H_2 \rightarrow \gamma\gamma) \sim 40 \text{ GeV}$ , one needs  $|S_{H_2}^{\gamma(F)}|^2 \sim 10^6$  which requires unlikely large value of  $Q_F \gtrsim 10$  with  $g_{s\bar{F}F}^S \sim 1$  and  $m_F = 400\text{-}500 \text{ GeV}$ . If  $Q_F \sim \mathcal{O}(1)$ ,  $\Gamma(H_2 \rightarrow \gamma\gamma)$  is significantly smaller than 1 GeV since  $|S_{H_2}^{\gamma(F)}|^2 \propto Q_F^4$ . On the other hand, to have  $\Gamma(H_2 \rightarrow gg) \sim 40 \text{ GeV}$ , one needs  $|S_{H_2}^{g(Q)}|^2 \sim 4 \times 10^2$  which results in  $\sigma(gg \rightarrow H_2) \sim 5 \times 10^5 \text{ fb}$  leading to enormous number of di-jet events with  $B(H_2 \rightarrow gg) \sim 1$ . Therefore, one may need to have

$$\Gamma_{H_2} \sim \Gamma_{H_2}^{\text{non-SM}} \sim 40 \text{ GeV}. \quad (17)$$

Secondly, we note that  $|S_{H_2}^{g(Q)} S_{H_2}^{\gamma(F)}| \sim 90$  to accommodate  $\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow \gamma\gamma) \sim 10 \text{ fb}$ . Our representative choice of  $S_{H_2}^{g(Q)} = 3$  can be easily realized if there are about 6 VLQs with  $m_Q \sim 400\text{-}500 \text{ GeV}$  and  $g_{s\bar{Q}Q}^S \sim 1$ . Usually  $|S_{H_2}^{\gamma(F)}|$  is larger than  $|S_{H_2}^{g(Q)}|$  enhanced by the  $2N_C Q_F^2$  factor together with additional contributions from VLLs. Therefore  $S_{H_2}^{\gamma(F)} = 10 \times S_{H_2}^{g(Q)} = 30$  could be a reasonable choice.

Bearing all theses observations, in Fig. 1, we show the decay width  $\Gamma_{H_2}$  (upper left), the cross section  $\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow \gamma\gamma)$  (upper right), and the ratios  $C_{H_1}^{g,\gamma}$  (lower) as functions of  $\sin \alpha$  taking  $S^{g(Q)} = 3$ ,  $S^{\gamma(F)} = 10 \times S^{g(Q)} = 30$ , and  $\Gamma_{H_2}^{\text{non-SM}} = 40 \text{ GeV}$ . In the lower frames, the solid (dashed) lines are for  $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$  (1). We observe that the suggested scenario comfortably explains the properties of the 750 GeV di-photon resonance



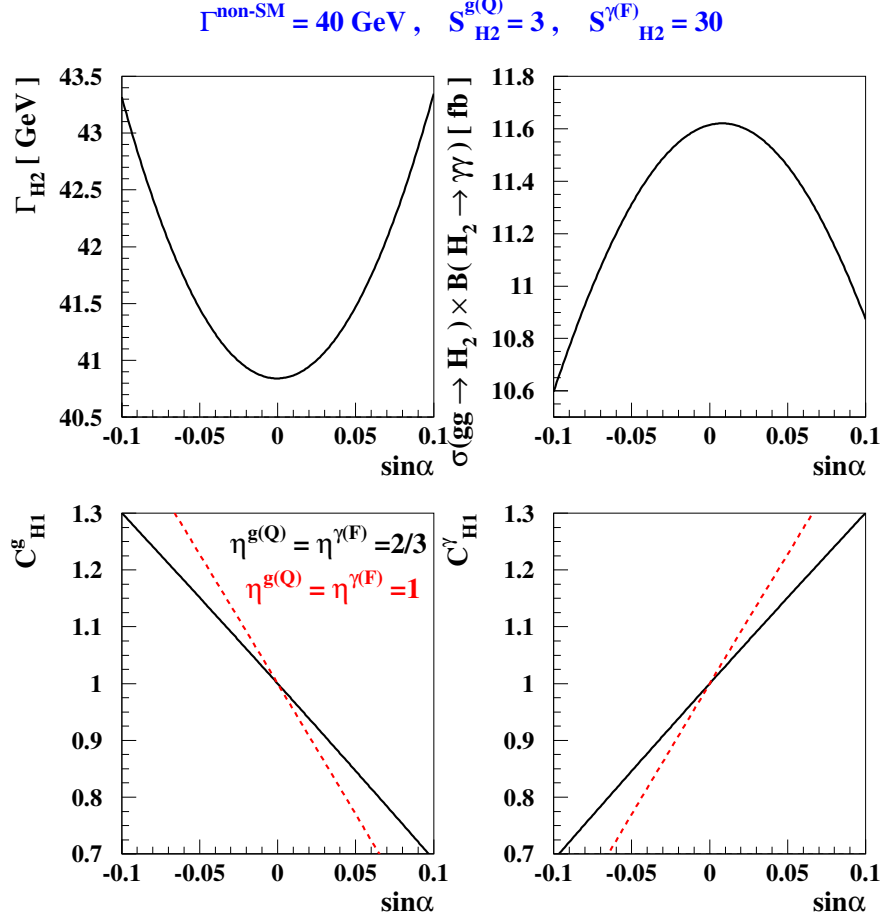


FIG. 1. The decay width  $\Gamma_{H_2}$  (upper left),  $\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow \gamma\gamma)$  (upper right), and the ratios  $C_{H_1}^{g,\gamma}$  (lower) as functions of  $\sin \alpha$ . We have taken  $S^{g(Q)} = 3$ ,  $S^{\gamma(F)} = 10 \times S^{g(Q)} = 30$ , and  $\Gamma_{H_2}^{\text{non-SM}} = 40 \text{ GeV}$ . In the lower frames, the solid (dashed) lines are for  $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$  (1).

without any conflict with the precision data on 125 GeV Higgs. A full model-independent precision analysis of the 125-GeV Higgs and 750-GeV resonance data is to be addressed in a future publication [31].

Though we have concentrated on the case of  $|\sin \alpha| < 0.1$ , we find our solution with  $S^{g(Q)} = 3$  and  $S^{\gamma(F)} = 30$  remains to be valid up to  $|\sin \alpha| \sim 0.4$  which is still allowed according to our global fits to the Higgs-portal type models [18], see Fig 2. We fix  $\Gamma_{H_2} = 45 \text{ GeV}$  and tune  $\Gamma_{H_2}^{\text{non-SM}}$  to accommodate it. And a general possibility of having  $\eta^{g(Q)} = \eta^{\gamma(F)} = 0$  is considered to satisfy the results of the global fits to the 125 GeV Higgs boson data. In this case, we note that  $\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow \gamma\gamma) \propto \cos^4 \alpha$  and  $C_{H_1}^{g,\gamma} = \cos \alpha$ .

In the following, we would like to comment on  $H_2$  decays into  $WW$ ,  $ZZ$ ,  $t\bar{t}$ , and  $gg$ . First,

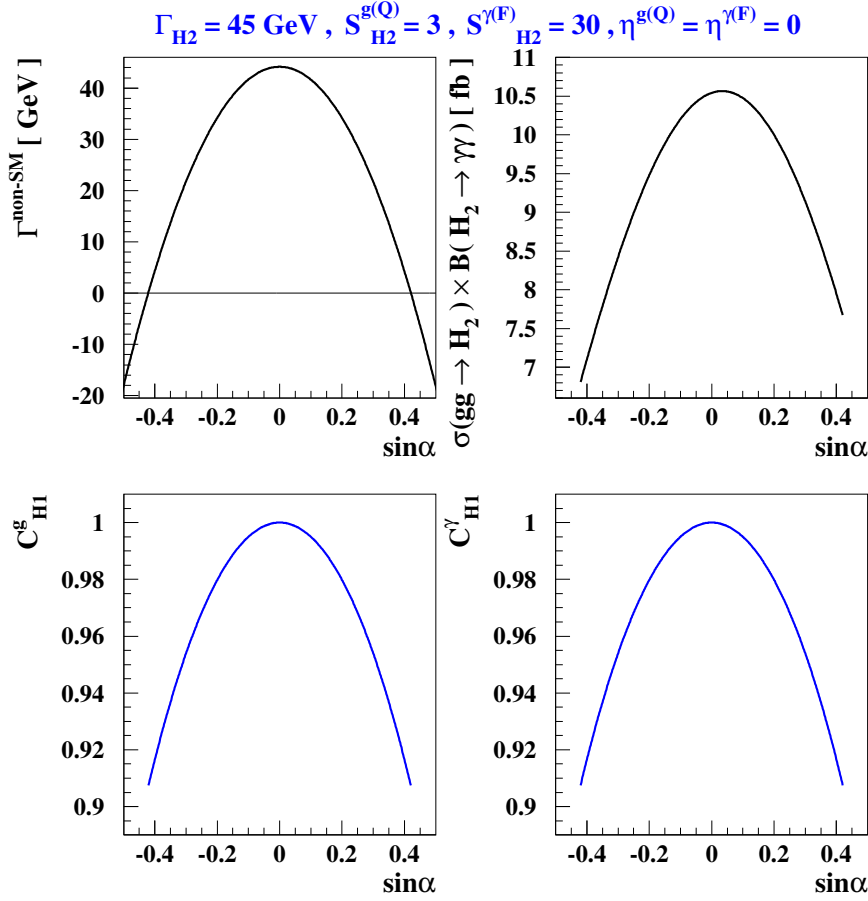


FIG. 2. The non-SM decay width  $\Gamma_{H_2}^{\text{non-SM}}$  (upper left),  $\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow \gamma\gamma)$  (upper right), and the ratios  $C_{H_1}^{g,\gamma}$  (lower) as functions of  $\sin \alpha$ . We have taken  $S_{H_2}^{g(Q)} = 3$ ,  $S_{H_2}^{\gamma(F)} = 30$ , and  $\Gamma_{H_2} = 45$  GeV. In the upper-right and lower frames, the physical condition  $\Gamma_{H_2}^{\text{non-SM}} > 0$  is imposed.

let us consider the case where  $H_2$  is produced through the SM-singlet VLQs which only have couplings to  $g$  and  $\gamma$ . In this limit of no interactions between VLQs with the  $W/Z$  boson,  $H_2$  decays into  $WW$ ,  $ZZ$ , and  $t\bar{t}$  through its SM Higgs component at the tree level while the decay into  $gg$  proceeds through the VLQ loops. In this case, the cross section times branching ratios are

$$\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow WW) \simeq 400 \text{ fb} \left( \frac{S_{H_2}^{g(Q)}}{3} \right)^2 \left( \frac{\sin \alpha}{0.1} \right)^2 \left( \frac{40 \text{ GeV}}{\Gamma_{H_2}} \right) \left( \frac{\sigma_{\text{SM}}(gg \rightarrow H_2)}{800 \text{ fb}} \right),$$

$$\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow ZZ) \simeq 200 \text{ fb} \left( \frac{S_{H_2}^{g(Q)}}{3} \right)^2 \left( \frac{\sin \alpha}{0.1} \right)^2 \left( \frac{40 \text{ GeV}}{\Gamma_{H_2}} \right) \left( \frac{\sigma_{\text{SM}}(gg \rightarrow H_2)}{800 \text{ fb}} \right),$$

$$\begin{aligned}\sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow t\bar{t}) &\simeq 90 \text{ fb} \left( \frac{S_{H_2}^{g(Q)}}{3} \right)^2 \left( \frac{\sin \alpha}{0.1} \right)^2 \left( \frac{40 \text{ GeV}}{\Gamma_{H_2}} \right) \left( \frac{\sigma_{\text{SM}}(gg \rightarrow H_2)}{800 \text{ fb}} \right), \\ \sigma(gg \rightarrow H_2) \times B(H_2 \rightarrow gg) &\simeq 200 \text{ fb} \left( \frac{S_{H_2}^{g(Q)}}{3} \right)^4 \left( \frac{40 \text{ GeV}}{\Gamma_{H_2}} \right) \left( \frac{\sigma_{\text{SM}}(gg \rightarrow H_2)}{800 \text{ fb}} \right).\end{aligned}\quad (18)$$

Given that the current upper limits on production of a resonance into a  $ZZ$ ,  $WZ$ , or  $WW$  pair is about  $150 - 200 \text{ fb}$  for  $M_X = 750 \text{ GeV}$  at  $\sqrt{s} = 13 \text{ TeV}$  [32], our scenario is more or less safe if  $|\sin \alpha| \lesssim 0.1$ . At  $\sqrt{s} = 13 \text{ TeV}$ , the search for di-jet resonances did not cover the di-jet mass range below  $1 \text{ TeV}$ , and we did not find any search for  $t\bar{t}$  resonances.

On the other hand, at  $\sqrt{s} = 8 \text{ TeV}$ , the gluon-fusion production cross section for a SM Higgs boson of  $750 \text{ GeV}$  is about  $150 \text{ fb}$  [33]. A combined search for  $WW, WZ, ZZ$  resonances has placed an upper limit of  $\sigma(pp \rightarrow G^*) \times B(G^* \rightarrow VV)$  at slightly less than  $100 \text{ fb}$  for  $M_{G^*} \approx 750 \text{ GeV}$  [34]. Therefore, the parameter regions of  $|\sin \alpha| \lesssim 0.1$  are perfectly safe with this  $8 \text{ TeV}$  search. Another search for  $t\bar{t}$  resonances put an upper limit of  $\sigma(pp \rightarrow X) \times B(X \rightarrow t\bar{t})$  at about  $0.5 - 1 \text{ pb}$  for a few models [35], which is again very safe for our scenario. Yet, another search for di-jet resonances [36] only covered the mass range from  $0.85 \text{ TeV}$  and up. At  $0.85 \text{ TeV}$ , the production rate limit is  $1 - 2 \text{ pb}$ , which hardly affects our scenario.

In general there can exist interactions between VLFs and  $W/Z$  bosons. To be specific, we consider the case in which VLQs share the SM  $SU(2)$  and  $U(1)_Y$  interactions. Then, in the limit of very small  $\sin \alpha$ , the decay of  $H_2$  into  $WW$  as well as those into  $ZZ$ ,  $Z\gamma$  and  $\gamma\gamma$  are dominated by the loops of VLQs. These loop-induced decay modes, especially the  $WW$  mode, are more model dependent than those into two gluons and two photons and we consider two representative scenarios for the interactions between VLQs with  $W/Z$  bosons.

In the scenario where VLQs are  $SU(2)$  singlets with only hypercharge interactions, they do not couple to the  $W$  boson. While their interactions with the photon and the  $Z$  boson are described by

$$\mathcal{L}_{VLQ} = -eQ_{VLQ} \bar{Q} \gamma^\mu Q A_\mu - \frac{e}{s_W c_W} (-Q_{VLQ} s_W^2) \bar{Q} \gamma^\mu Q Z_\mu, \quad (19)$$

where we are taking  $e > 0$  with  $s_W \equiv \sin \theta_W$ ,  $c_W \equiv \cos \theta_W$ , and  $t_W = s_W/c_W$ . We find that the effective vertices involving  $H_2 \gamma \gamma$ ,  $H_2 Z \gamma$ , and  $H_2 ZZ$  can be written as, up to an overall constant,

$$\mathcal{L} \propto H_2 \left( F_{\mu\nu} F^{\mu\nu} + t_W F_{\mu\nu} Z^{\mu\nu} + t_W^2 Z_{\mu\nu} Z^{\mu\nu} \right), \quad (20)$$

and the ratio  $\Gamma(H_2 \rightarrow ZZ) : \Gamma(H_2 \rightarrow Z\gamma) : \Gamma(H_2 \rightarrow \gamma\gamma)$  is approximately given by

$$\Gamma(H_2 \rightarrow ZZ) : \Gamma(H_2 \rightarrow Z\gamma) : \Gamma(H_2 \rightarrow \gamma\gamma) \approx t_W^4 : 2t_W^2 : 1, \quad (21)$$

ignoring the  $Z$ -boson mass in the final state. Taking  $t_W \approx 0.55$ , the ratio is  $0.09 : 0.6 : 1$ . For  $\sigma(pp \rightarrow H_2 \rightarrow \gamma\gamma) \sim 10$  fb, we have  $\sigma(pp \rightarrow H_2 \rightarrow ZZ) \approx 0.9$  fb and  $\sigma(pp \rightarrow H_2 \rightarrow Z\gamma) \approx 6$  fb which correspond to 1.4  $ZZ$  events and 130  $Z\gamma$  events using  $Z \rightarrow \ell^+\ell^-$  with an accumulated luminosity of  $300 \text{ fb}^{-1}$  in the future LHC.

In another scenario, we place one pair of VLQs  $U$  and  $D$  in an  $SU(2)$  doublet as  $(U, D)^T = (U, D)_L^T + (U, D)_R^T$  which carries hypercharge  $Y$ . Then the electric charges are given by  $Q_U = T_{3U} + Y$  and  $Q_D = T_{3D} + Y$  and we have  $Q_U - Q_D = 1$  independently of the hypercharge  $Y$ . Note we are taking  $T_{3U} = -T_{3D} = 1/2$ . In this case the interactions of the VLQs with gauge bosons are given by

$$\begin{aligned} \mathcal{L}_{VLQ} = & -e \left( Q_U \bar{U} \gamma^\mu U + Q_D \bar{D} \gamma^\mu D \right) A_\mu \\ & - \frac{e}{s_W c_W} \left[ \bar{U} \gamma^\mu U (T_{3U} - Q_U s_W^2) + \bar{D} \gamma^\mu D (T_{3D} - Q_D s_W^2) \right] Z_\mu \\ & - \frac{e}{\sqrt{2} s_W} \left( \bar{U} \gamma^\mu D W_\mu^+ + \bar{D} \gamma^\mu U W_\mu^- \right). \end{aligned} \quad (22)$$

We note the couplings to the  $Z$  boson are purely vector-like and proportional to the factors  $T_{3U,3D} - Q_{U,D} s_W^2$  which are different from the SM case where only the left-handed quarks are participating in the  $SU(2)$  interaction. It is possible to make a precise prediction in a simpler case in which, for example,  $Y = 0$ <sup>§</sup>:

$$\Gamma(H_2 \rightarrow WW) : \Gamma(H_2 \rightarrow ZZ) : \Gamma(H_2 \rightarrow \gamma Z) : \Gamma(H_2 \rightarrow \gamma\gamma) \approx \frac{1}{2s_W^4(Q_U^2 + Q_D^2)^2} : \frac{1}{t_W^4} : \frac{2}{t_W^2} : 1, \quad (23)$$

ignoring the  $W$ - and  $Z$ -boson masses. Taking  $s_W^2 \approx 0.23$  and  $Q_{U,D}^2 = 1/4$ , we find the ratio is  $38 : 11 : 6.6 : 1$ . For  $\sigma(pp \rightarrow H_2 \rightarrow \gamma\gamma) \sim 10$  fb, we have  $\sigma(pp \rightarrow H_2 \rightarrow WW) \approx 380$  fb,  $\sigma(pp \rightarrow H_2 \rightarrow ZZ) \approx 110$  fb, and  $\sigma(pp \rightarrow H_2 \rightarrow Z\gamma) \approx 66$  fb which correspond to 5400  $WW$  events, 180  $ZZ$  events, and 1400  $Z\gamma$  events using  $Z \rightarrow \ell^+\ell^-$  and  $W \rightarrow \ell\nu$  with an accumulated luminosity of  $300 \text{ fb}^{-1}$  in the future LHC. This scenario is much more promising to probe compared to the previous one

<sup>§</sup> We find a complete agreement between our results and those presented in Ref. [40]. A more detailed study considering various scenarios will be presented in Ref. [31].

Before concluding, we would like to make a comment on the LHC constraints on VLQs. The VLQs have been actively searched for at the LHC. For example, the ATLAS and CMS collaborations carried out searches recently at  $\sqrt{s} = 13$  TeV [37, 38] and there was another one at 8 TeV [39]. The lower limits on VLQ mass range from about 750 GeV to about 1.7 TeV, depending on decay channels. Such channels include  $\text{VLQ} \rightarrow bW, Zt, Ht$ . Note that all the particles in the final states are visible and energetic because the mass differences between the VLQ and decay products are assumed to be large enough. Furthermore, the branching ratio into a chosen decay channel is assumed 100%. However, if the VLQ decays into invisible particles, e.g., dark matter, and other SM particles, and also if the mass difference between the VLQ and dark matter is small, then the energy available for the visible particles would be small. In these cases, the search would be more subtle and the constraints on VLQ can be significantly relaxed, such that a VLQ of mass as low as 400 GeV might evade the LHC constraints.

#### IV. CONCLUSIONS

The hint of a potential 750 GeV particle observed by ATLAS and CMS is very intriguing. At the surface value of the large production cross section, it is hard to interpret it in the conventional Higgs extension models, such as 2HDMs or MSSM. However, if the additional particles exist, e.g. vector-like fermions which are allowed to run in the  $H_2\gamma\gamma$  and  $H_2gg$  vertex, it is possible to explain the large cross section and relatively large total width of the particle.

In this work, we have investigated the models with a singlet scalar that has renormalizable couplings to the vector-like leptons and quarks, taking fully account of the doublet-singlet mixing. We have used the allowed parameter space regions that we obtained in recent global fits to the Higgs boson data. In the allowed space, we actually find solutions to the 750 GeV boson with  $|\sin\alpha| \lesssim 0.1$ ,  $\Gamma_{H_2} \sim \Gamma(H_2 \rightarrow H_1 H_1) + \Delta\Gamma_{\text{inv}}^{H_2} \sim 40$  GeV, and  $|S_{H_2}^{g(Q)} S_{H_2}^{\gamma(F)}| \sim 90$ . It remains to be seen if this excess will survive more data accumulation in the near future. Should the fitted cross section from the LHC experiments increases or decreases in the future, we can simply modify the product  $|S_{H_2}^{g(Q)} S_{H_2}^{\gamma(F)}|$  to fit to it. If the 750 GeV excess turns out to be a new particle, new vector-like fermions may accompany and could be of utter importance at the LHC Run II.

As shown in this work, when the total decay width of the 750 GeV di-photon resonance is sizable, it would decay dominantly into invisible particles, which could give rise to monojet events with an additional gluon radiated from the initial-state gluons. Monojet events have been searched actively at the LHC, e.g., at  $\sqrt{s} = 13$  TeV [41] and at  $\sqrt{s} = 8$  TeV [42] by ATLAS (CMS has similar results), in which the 95% CL upper limits on monojet production cross sections due to DM are given. Let us focus on the 13 TeV data and, to be more specific, on a particular selection cut – IM1 ( $E_T > 250$  GeV and  $P_{T_j} > 250$  GeV). It gives an upper limit of  $\sigma \times \text{Acceptance} \times \text{Efficiency} = 553$  fb. On the other hand, the production cross section of  $H_2$  via gluon fusion is  $\sigma(gg \rightarrow H_2) \sim 10^4$  fb, see the first equation in Eq. (16). In order to radiate an additional energetic gluon from the initial-state gluons, the cross section would decrease by a factor of  $\alpha_s/2\pi \sim 10^{-2}$ . Therefore, we expect a cross section of order  $10^2$  fb for monojet production which is obviously below the current experimental upper limit. We find that the case at 8 TeV would be similar. Therefore, the current production of  $H_2$ , which decays dominantly into DM, would still be consistent with the monojet searches at the LHC ¶.

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¶ Also this channel is dependent on the UV completion of DM models as well as DM being scalar, fermion or vector boson for scalar mediator cases (for example, see Ref. [43] for the Higgs portal DM case).

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